Development of a 1.5KW High Specific Impulse Magnetic Shielded Hall Thruster

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Abstract: This paper presents the design, development and test results of a high specific impulse 1.5KW Magnetic Shileded hall thruster. Magnetic shielding is achieved by reconfiguring the magnetic circuit compared to non magnetic shielded design. The weak magnetic flux lines from near anode are taken out to graze the ceramic liners. Also, both the liners shape are chamfered accordingly to make these flux lines nearly parallel to the ceramic surface around the channel exit. F criteria is calculated and optimized to have good ionization efficiency. Finally, twenty five hours testing is carried out and erosion of ceramic liner is assessed.

Nomenclature

$\emptyset$	=	Electric Potential
$\emptyset_{\mathbf{0}}$	=	Electric Potential at the center of the channel
T_e	=	Electron Temperature
n	=	Plasma density
n_0	=	Plasma density at the center of the channel
F	=	Scalar F function
$\vec{B}$	=	Magnetic Flux Vector

I. Introduction

Electric Propulsion System has emerged as a game changing technology in satellite propulsion domain. Its ability to substantially reduce the launch mass and/or increase the payload capacity of the satellite has made it an attractive proposition when compared to traditional chemically propelled satellites. In Indian context, use of EPS can effectively mean launching a 6t class satellite using a 4t capable GSLV MKIII. Hall thrusters also called the Stationary Plasma Thrusters(SPTs) along with the Ion thrusters are the two most developed and flight proven technologies in electric propulsion. Studies have shown that hall thrusters are the better choice for GTO to GEO orbit raising applications [1]as it reduces transfer to a more acceptable period of 3-4 months whereas the time taken by Ion thrusters is 6-8 months for similar available onboard power and size of satellites.

Hall thrusters with all the benefits suffer from one critical disadvantage of having lower operational life of few thousands hours. The life of thruster is governed by the erosion of its ceramic guard liners which protect the magnetic pole pieces from impact of high energy Xenon ions accelerated by the plasma. Magnetic Shielding first noticed in BPT-4000[2] and later proven in H6MS [3-7] addressed this shortfall in Hall thrusters and the technique

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was successful in removing erosion of liner material as a failure mode. Hall thrusters with Magnetic Shielding are currently being designed both in low power and high power ranges[7-10].

LPSC, the lead propulsion design center of ISRO, designed and qualified a non-shielded 1.5KW SPT with Isp of 2100s and predicted life of 4000hours. The thruster produces a thrust of 75mN at nominal xenon flow rate of 3.3 mg/s for anode and has already undergone testing for 1000 hours. The operating voltage of 550V instead of the traditional 300V operation results in Isp exceeding 2000s. However, higher operating voltage results in increase of erosion rate, therefore expected life of this thruster is less when compared to SPT-100 which works at 300V. The present work aims at achieving the life of thruster in excess of 20000 Hrs while maintaining similar performance of the thruster.

Figure 1. 1.5KW SPT firing at Vacuum Chamber at LPSC

II. Design of the Magnetic Shielded SPT

The 1.5KW SPT acted as the base model for design of the MS configuration. The channel dimensions, anode gas distributer, cathode type and its placement location are kept same as that of the non magnetic shielded design. The magnetic field configuration is however modified to convert the thruster into a magnetic shielded one.

A. Magnetic Circuit Design

Magnetic field profile design is the most crucial factor which decides the performance and life of the thruster. The positive axial gradient and magnetic lens shape is considered ideal for efficient operation of the SPT. Magnetic lens is effective in limiting the wasteful electron current but is not completely effective in curtailing erosion of the liners from impingement of high speed xenon ions.

The current magnetic field design results in higher electron temperature, T_e in the exit region of the SPT. The electrons have been experimentally found to be near isothermal in SPTs. This means along the magnetic field line in radial direction, electron temperature remains same and electric potential along the magnetic field line is governed by the eq. (1). The impact of high electron temperature is that electric potential no longer remains equipotential in the radial direction. This results in generation of significant radial electric field component along with the predominant axial electric field. The ions created near ceramic liner boundary of the thruster no longer have perfect axial vector and therefore impinge the liner surface resulting in erosion.

$$\emptyset = \emptyset_0 - T_e \ln \frac{n}{n_0} \quad (1)$$

Magnetic shielding minimizes the electron temperature and achieves equipotential along the field lines near channel boundary by reconfiguring the magnetic field lines. The magnetic flux lines from inside the channel are brought to graze the ceramic boundary. The effect of such design is the pushing of axial magnetic field maximum location outside the thruster exit boundary. It is experimentally seen that MS design have slightly less efficiency when compared to non magnetic shielded SPT due to much higher Xe^{2+} and Xe^{3+} ions constitutions and greater plume divergence angle. The reason is attributed to higher electron temperature in the ionization zone as its effective cooling is reduced due to reduction in SEE. Currently there is no proper criteria to define how much the magnetic field maximum should be moved out to optimize both erosion as well as efficiency. Previous work includes use of complex plasma models[5] to simulate entire working of Hall thrusters.

Here, the F scalar function shown in eq. 2 defined by Gorshkov in Ref. 11, is also utilized to configure MS shielded design. F function's maximum is considered to coincide with the ionization zone and its placement near the annular channel center of SPT is considered optimum for high thrust efficiency. Also, the acceleration zone of ions experimentally has been found to start in the immediate downstream of F maximum [11]. Therefore, the MS design was carried out with two objectives of keeping the F function in the channel center and moving it out only enough so that acceleration zone just begins after the pole piece covering ceramic zone.

$$\boldsymbol{F} = \left| \frac{\vec{B} \times \nabla |\vec{B}|}{\vec{B}} \right| \quad (2)$$

B. Magnetic Shielded SPT Magnetic Profile Simulation

Ansys Maxwell software is used to simulate a 2D magnetic circuit. Fig. 2 shows the simulated F scalar function for the non magnetic shielded thruster. The measured erosion start locations in the actual thruster is pointed out in the figure. The erosion can be seen to start in the immediate downstream of the F function maxima and flux lines passing through the F maxima coincide with the erosion start point. Here the F maxima is located well inside the channel and slightly biased towards the inner ceramic. The magnetic shielded thruster simulated F scalar function is shown in Fig. 3. The max F location is moved downstream and more towards channel center in this design. The chamfering of the ceramic liners is done roughly according to the magnetic flux lines passing through the max F zone. However, for manufacturing ease, the inner ring was given reduced chamfering (not shown in fig. 3) from mid-section. It is therefore expected that inner ring might show some erosion at rated power in downstream zone.

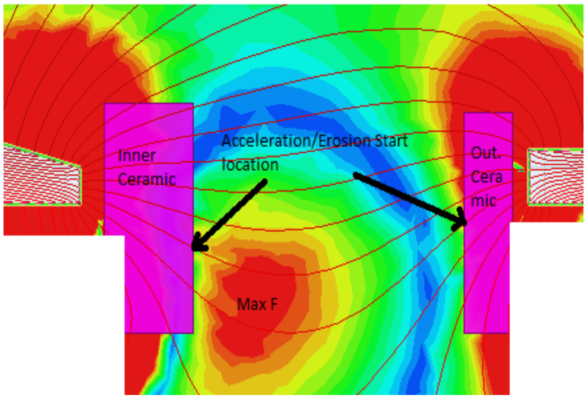

Figure 2. Simulated F scalar function for non magnetic shielded design.

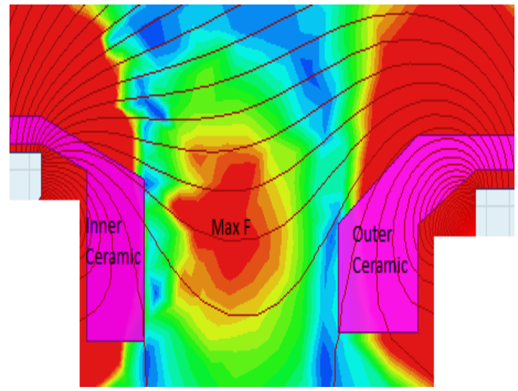

Figure 3. Simulated F scalar function for Magnetic shielded design.

Fig. 4 shows the radial magnetic field profile along the channel center line for the two designs. As a result of new profile shape, it is observed that the magnetic field maxima has shifted downstream and is located outside the channel. The slope is kept roughly similar to the non-magnetic shielded thruster.

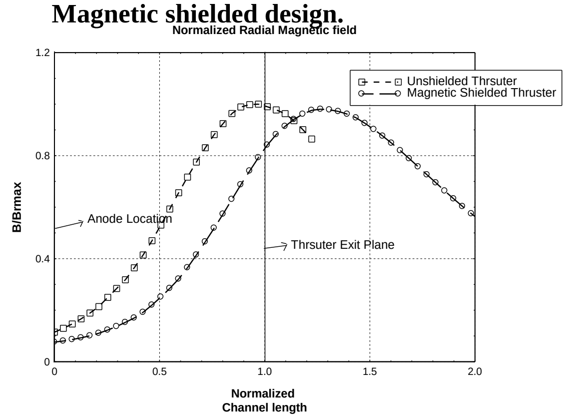

Figure 4. Simulated Normalized radial magnetic field alongthe channel centerline.

III. Experimental Apparatus

A. Magnetic shielded SPT Thruster

The thruster parts are fabricated keeping in mind the ease of modification and reassembly if required. The $BNSiO_2$ ceramic liners are designed to completely encapsulate both the pole pieces. The current design takes care of expected pole piece face erosion reported in Ref. 12. The anode gas distributer is fabricated with multiple small radial holes to uniformly distribute the Xenon gas in the channel. The magnetic circuit was fabricated with soft iron material. One inner and four outer coils were wound with high temperature winding wires rated for 500C. Fig 5. shows the image of the assembled MS thruster after 25 hours of testing. The ceramics and pole pieces are held in position with the one central

Figure 5. MS thruster after testing for 25 Hours

screw and 4 outer screws. A Barium Oxide based cathode capable of supplying up to 6A of current was assembled with the anode unit. The position of the cathode with respect to anode was kept unchanged when compared with the non-magnetic shielded base design.

B. Vacuum Chamber

The thruster is tested at small vacuum chamber at LPSC, Trivandrum. The chamber is 2m in diameterand4m in length with a pumping capacity of 30000 liters of xenon. The chamber wall is made of stainless steel. Background pressure better than $2x10^{-5}$mbar of xenon is always maintained during the test with the help of cryogenic pumps and three cryo heads. This makes chamber suitable for testing of this power range of thruster continuously for couple of hours. Fig. 6 shows the image of the vacuum chamber installed at LPSC.

C. Magnetic Field Measurement Setup

Magnetic field measurements are carried out using a setup shown in fig.7. A gauss probe mounted on a height gauge capable of back and forth as well as up and down precise motion with accuracy better than 0.1mm. The thruster is kept on a rotary table for measuring different azimuthal positions. The profiles are measured both radially as well as axially in steps of 1 mm at 4 different azimuthal locations in the annular channel separated by 90^0 and compared for uniformity as well as with the designed value.

Figure 6. Vacuum Chamber

Figure 7. Magnetic Field Measurement Setup

IV.Test Procedure

The thruster after assembly undergoes electrical checks to verify the continuity, isolation and electrical resistances. Calibrated digital multi meter as well as Megger are used to carry the above checks. The thruster is mounted in the chamber for testing. Electrical connections with rated power supplies for anode, magnets, heater and igniter are established. A 2µF capacitor is used between anode power supply and the thruster. Discharge current oscillations are measured with hall sensors. Initial few hours firing is carried out for outgassing of the thruster.

V. Results and Discussion

A. Measured Magnetic Field

The thruster is mounted on a rotary table and gauss probe was mounted on a height gauge. Figure 8 shows the measured radial magnetic field along the centerline of the thruster. The location of the peak of the measured profile matches with simulated profile peak location. However, some difference in slope and magnitude of peak magnetic field was noticed with respect to the simulated profile. The difference is attributed to the saturation of magnet coils at higher currents. It was however decided to proceed with the initial tests and subsequently redesign the coils for future testing if erosion of liners seen.

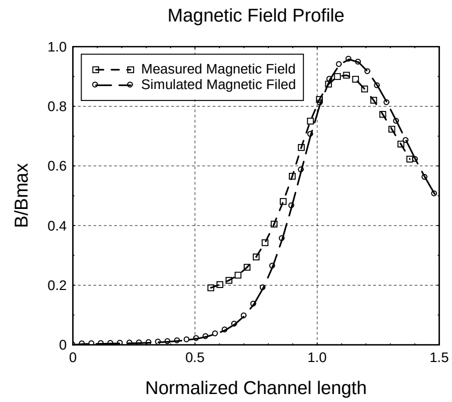

Figure 8. Comparison of measured and simulated radial magnetic field along the centerline of the thruster

B. Erosion of the ceramic rings

The thruster is tested for the cumulative duration of 25 hours with 20 hours testing done at rated power. Visual inspection of the thruster is carried out after the tests for qualitative assessment of erosion. The outer ceramic liner as shown in fig.9 shows no appreciable erosion after 25 hours of cumulative testing. The deposit of black carbon over almost entire exposed part of the outer ring confirms this assessment. The inner ceramic liner shown in figure 10 shows no erosion in the cylindrical area but shows slight erosion in the chamfered area. However, it can be clearly inferred from the drawing of the inner liner that the eroded area is well downstream of the of inner pole piece location and therefore poses no risk of exposure of inner pole.

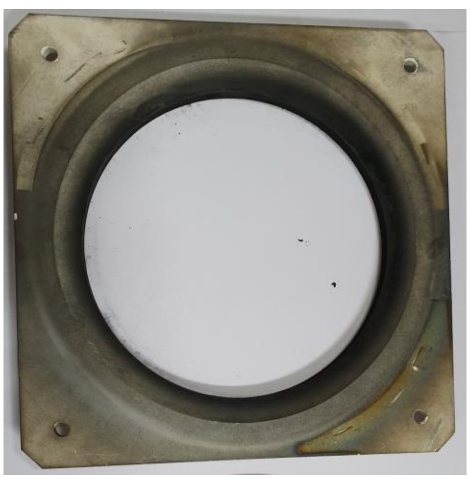

Figure 9. Outer Ceramic Ring after 25 hours of testing

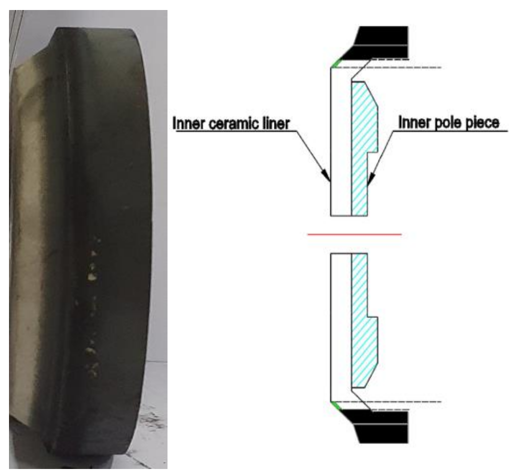

Figure 10. Inner Ceramic Ring after 25 hours of testing(Left), Drawing of the inner liner with Inner pole piece(Right)

Fig. 11 shows the front view of the inner liner. It can be seen that slight erosion is witnessed on the liner face consistent with the results shown in Ref. 12. The cause of liner face erosion is understood to be the highly concentrated magnetic flux lines entering the pole face in the MS approach which guide some of the ions to hit the front face of liner. However, use of $BNSiO_2$ material as liner extension to cover the pole piece significantly reduces this rate of erosion when compared with the totally exposed metal pole piece.

Figure 11. Inner Ceramic Liner(Front View)

C. Discharge Parameters

Preliminary testing of 25 hours of thruster is carried out with primary objective of demonstrating magnetic shielded principle. Therefore, thrust measurement and plume diagnostics were not carried out as part of this campaign. However, voltage and flow variation test were performed to establish the working envelop of the thruster. Fig. 12 shows the mean discharge current vs voltage graph. The thruster was tested for voltage varying from 300V to 550V in steps of 50V and anode flow from 2mg/s, 2.5mg/s, 3mg/s and 3.3mg/s. Thruster was allowed to fire for at least 15 minutes and then the readings were taken. The cathode flow was kept fixed at 0.2 mg/s throughout this test. The vacuum level was continuously monitored and it remained in the range of 1-2x10^{-5}mbar of Xenon. Discharge current oscillations were monitored and the primary breathing mode frequency was recorded for the full power operation of 550V and 3.3 mg/s and was equal to 19 kHz. Fig. 13 shows the screen shot of the oscilloscope displaying the FFT result. The obtained discharge currents are similar to the values obtained in the non-magnetic shielded design with thruster firing is in stable breathing oscillations mode. Therefore, it is expected that performance parameters like thrust, Isp and efficiency will not vary significantly.

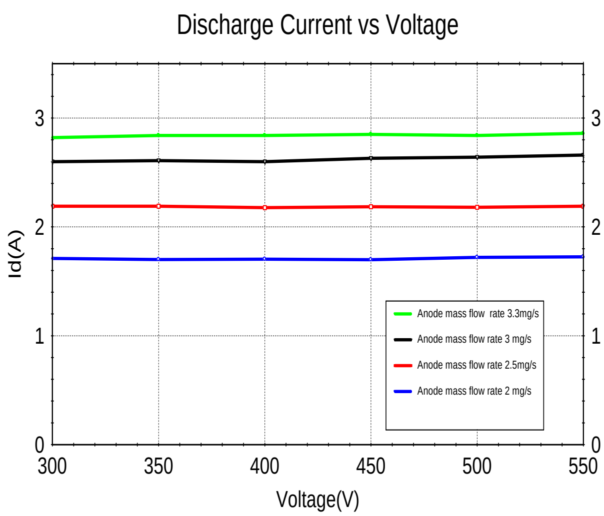

Figure 12. Mean discharge Current vs voltage

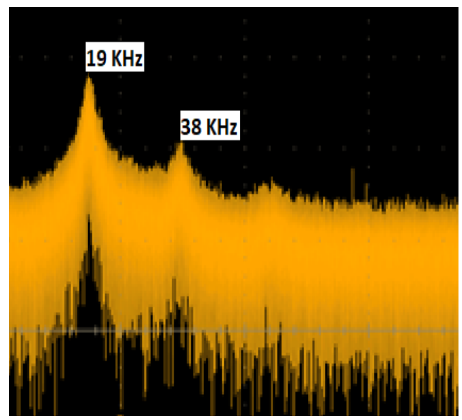

Figure 13. FFT of the Discharge Current @550V and 3.3 mg/s anode flow rate

IV. Conclusion

The magnetic shielded principle is successfully demonstrated in the new design with thruster operation in power range of 450W to 1600W.The efficacy of use of F criteria is ascertained to an extent as thruster is both magnetically shielded as well as discharge parameters obtained are similar to the non-magnetic shielded design. Quantitative measurement of erosion of ceramic rings are planned to be carried out after 50 hours of testing. It is now planned to extensively characterize this thruster with measurement of thrust and plume parameters. It is expected that unique feature of complete encapsulation of the pole piece with $BNSiO_2$, in addition to inhibiting magnetic pole face erosion, helps in reducing the electron temperature in the ionization zone as the strong magnetic flux lines still pass through the ceramic material, producing secondary electrons. The change of magnetic circuit is also planned to further increase the magnetic field strength to operate the thruster at voltages up-to 800V.

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